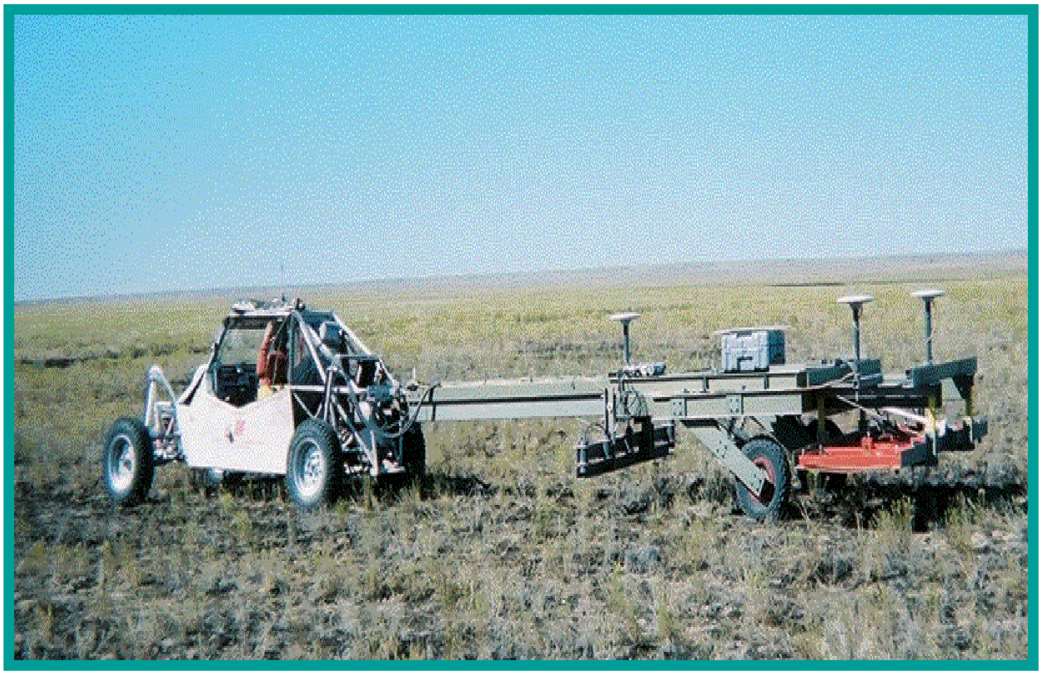
ESTCP
Cost and Performance Report

(MM-0531)



Simultaneous Magnetometer and EM61 MK2 Vehicle-Towed Array for Wide Area Assessment

May 2008

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ACRONYMS AND ABBREVIATIONS

APG	Aberdeen Proving Grounds (Maryland)
ATC	Aberdeen Test Center
BRAC	base realignment and closure
CEHNC	U.S. Army Corps of Engineers Engineering and Support Center, Huntsville
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
COTS	commercial off-the-shelf
CRADA	Cooperative Research and Development Agreement
DGM	Digital Geophysical Mapping
DSB	Defense Sciences Board
EM	electromagnetic
EMI	Electromagnetic Induction
EOD	Explosive Ordnance Disposal
EOTI	Explosive Ordnance Technologies Inc.
EQT	Environmental Quality Technology
ERDC	Engineer Research and Development Center
ESTCP	Environmental Security Technology Certification Program
FUDS	Formerly Used Defense Sites
GPS	global positioning system
LIDAR	Laser Imaging Detection and Ranging
MEC	munitions and explosives of concern
MMRP	Military Munitions Response Program
MPC	Magnetometer Period Counter
MTADS	Multisensor Towed Anomaly Detection System
NAOC	National Association of Ordnance Contractors
NAVEODTECHCEN	Naval Explosive Ordnance Technology Center
NRL	Naval Research Laboratory
ODC	Other Direct Costs
PBR	Precision Bombing Range
PI	principal investigator
PPS	pulse per second

ACRONYMS AND ABBREVIATIONS (continued)

PRR	Program Requirements Review
ROM	Rough Order of Magnitude
RTK	real-time kinematic
SAIC	Science Applications International Corporation
SNR	signal-to-noise
SORT	Simulated Oil Refinery Target
STOLS	Surface Towed Ordnance Locator System
USACE	U.S. Army Corps of Engineers
UXO	unexploded ordnance
VSEMS	Vehicular Simultaneous EMI and Magnetometer System
VSP	Visual Sample Plan
WAA	Wide Area Assessment
YPG	Yuma Proving Grounds (Arizona)

ACKNOWLEDGEMENTS

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1.0 EXECUTIVE SUMMARY

1.1 BACKGROUND

One of the recommendations of the 2003 Defense Sciences Board (DSB) Report on Unexploded Ordnance (UXO) was to immediately assess the scope of ordnance contamination of roughly ten million acres of land on formerly used defense sites (FUDS) and base realignment and closure (BRAC) sites and rapidly ascertain what percentage of this acreage actually contains UXO. Airborne technologies are well-suited for acquiring data over sites comprising thousands of acres and assessing the degree of UXO contamination. In particular, helicopter-based magnetometry has been shown to be effective in detecting individual UXO objects of a range of sizes. However, because magnetic field strength falls off as one over the cube of the distance ($1/R^3$), the increased sensor height of helicopter-based sensors makes detection of objects smaller than 60 mm very difficult. The Geonics EM61 pulsed induction sensor, frequently the sensor of choice for ground-based UXO detection, has an even steeper ($1/R^6$) falloff, and for this reason has not been routinely employed in helicopter-based UXO detection. Further, there are limits to the safe terrain-following of helicopter-based systems. For these reasons, ground-based digital geophysical mapping (DGM) systems have a role to play in wide area assessment (WAA), both for close-in detection of object boundaries, as well as in validation and verification of the results from airborne surveys.

The technology used for this project—the Vehicular Simultaneous Electromagnetic Induction (EMI) and Magnetometer System (VSEMS), formerly known as the Simultaneous Multisensor Surface Towed Ordnance Locator System (STOLS) is a ground-based vehicle-towed array that collects total field magnetometer and EM61 data simultaneously in a single survey pass. The benefits of using a concurrent multisensor towed array are that (1) many sites contain surprises in the form of unexpected munitions or explosives of concern (MEC) or MEC-related activity, so choosing a sensor because of its detection characteristics may result in missing unexpected objects, and (2) since most common geology ("hot rocks") doesn't show up on the EM61, the presence of a confirming electromagnetic (EM) signature can be used as a highly effective geologic false alarm reduction tool. The use of VSEMS at the Kirtland WAA site yielded both of these advantages.

1.2 OBJECTIVES OF THE DEMONSTRATION

The stated objectives of the demonstration as listed in the Demonstration Plan were:

- To use VSEMS to collect magnetometer and EM61 DGM data on preplanned transects (generated by another contractor running Visual Sampling Plan [VSP] transect-planning software) so that the WAA project as a whole could use these data to refine bombing target locations, extents, and edges that were already approximately known from conceptual site models
- To visually inspect and interpret the transect-based data for the presence of bombing target edges or extent, or evidence of other subsurface entities such as trenches and pits, that might be of interest in a WAA context

- To extract anomaly locations and size estimates from the transect data and generate anomaly lists which, in turn, were fed to VSP to design further sets of transects
- To use VSEMS to collect and analyze full-coverage data over selected areas for validation purposes, extracting anomaly locations and depth and size estimates from the surveyed areas
- To visually inspect and interpret the full-coverage data for the presence of bombing target edges or extent, or evidence of other subsurface entities such as trenches and pits, that might be of interest in a WAA context
- To demonstrate and validate the use of VSEMS, which had been further improved over prior fieldings with the installation of a new EM61 Mk2 array, as a viable survey-ready DGM tool that consistently and reliably generates very high-quality concurrent EM61 and magnetometer data.

All of the above objectives were met. The system collected more than 350 acres of concurrent magnetometer and EM61 Mk2 data at the Former Kirtland Bombing and Gunnery Range, and these data were an asset to the WAA Pilot Program.

1.3 REGULATORY DRIVERS

The U.S. Army Corps of Engineers (USACE) is the lead agency under the FUDS program. USACE administers the FUDS Military Munitions Response Program (MMRP) using methods based on the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) process.

1.4 DEMONSTRATION RESULTS

- Data from the system helped to delineate edges of the three known bombing targets (N2, N3, and New Demolitions).
- Data from the system helped to discover previously unknown bombing targets around N3.
- The concurrent multisensor data was useful in screening out false alarms. Digging of a representative sample of items from all layers (not just VSEMS) revealed an 18% no-find rate, predominantly due to geology. The no-find rate in the 100% geophysical survey areas completed by VSEMS was 13.5%. Post-survey analysis revealed that a simple cross-correlation between the two sensors can further drop this rate dramatically. By requiring a confirming signature on the EM61, the probability of false alarm drops to less than 1%.
- The production rate, averaged across both transect surveys and 100% geophysical surveys, and averaged across all days in the field, was just under 10 acres per day.

1.5 STAKEHOLDER/END-USER ISSUES

To contractors, there were no stakeholder or end-user issues; the Environmental Security Technology Certification Program (ESTCP) Program Office was the interface to the stakeholders.

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2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY DEVELOPMENT AND APPLICATION

2.1.1 Background

The Vehicular Simultaneous EMI and Magnetometer System (VSEMS) used on this project was developed by Science Applications International Corporation (SAIC) with support from ESTCP under project MM-0208, implemented through a Cooperative Research and Development Agreement (CRADA) between SAIC and the USACE Huntsville Center (CEHNC). VSEMS is the only system in the world that simultaneously collects high-quality data from commercial off-the-shelf (COTS) total field magnetometers and COTS EM61 Mk2 pulsed induction sensors on a single towed platform. It substantially leveraged GEO-CENTERS' (now SAICs') existing Surface Towed Ordnance Locator System (STOLS) global positioning system (GPS)-integrated towed magnetometer array as a development platform, and augmented it with newly designed interleaving hardware, a new proof-of-concept, nonmetallic towed platform, and existing EM61 electronics and coils. Further development, which integrated modern Geonics EM61 Mk2 hardware, was funded by the U.S. Army Environmental Quality Technology (EQT) program and the Aberdeen Test Center (ATC).

2.1.2 Application to Various Types of UXO

Total field magnetometers excel at detection of large, deep ferrous objects, but may miss small shallow objects with low-ferrous content such as 20 mm and 40 mm projectiles. Pulsed induction sensors excel at detecting these objects but may miss the large deep objects due to the sensor's steeper response falloff with distance from the object. Because VSEMS uses both total field magnetometers and EM61 Mk2 pulsed induction sensors, it is applicable to all types of UXO typically of concern in a range clearance application.

2.2 PROCESS DESCRIPTION

2.2.1 Theory of Operation

Historically, simultaneous deployment of magnetometers and pulsed EM such as the Geonics EM61 on a common platform has not been possible due to the fact that the EM transmission pulse is asynchronous with the magnetometer sampling, and thus is picked up by the magnetometers as noise. Even at 10 ft—a practical separation distance for sensor co-location on a common towed platform—EM61-induced noise is over 100 nT, rendering concurrently collected magnetometer data useless.

Under ESTCP Project MM-0208, SAIC developed hardware that monitors the pulse from the EM61, waits a preset amount of time for the pulse and the secondary fields generated by the pulse to ring down, then samples the magnetometer for a short window. The newly developed Magnetometer Period Counter (MPC) board is designed to interleave the magnetometer and EM61 data acquisition cycles as follows. The MPC circuitry looks for the 1 pulse per second (PPS) from the GPS, then looks for the rising edge of the next EM61 transmission pulse. The system timing then uses a programmable waiting period and a sampling period. The 75 Hz EM61

transmission pulse comes in every 13.3 ms. The board waits 8 ms, at which point the EM61 transmission pulse has died off (this has been verified by direct measurement). The MPC board then samples the magnetometers for 5 ms, during the period in which the EM61s are not transmitting. In this way, the magnetometers are sampled only when the EM61s are quiet. The timing diagram for this interleaved synchronous data acquisition is shown in Figure 1. Note that in this new design, acquisition of magnetometer data is triggered by the receipt of a 75 Hz strobe from the EM61 electronics after the GPS' 1 PPS.

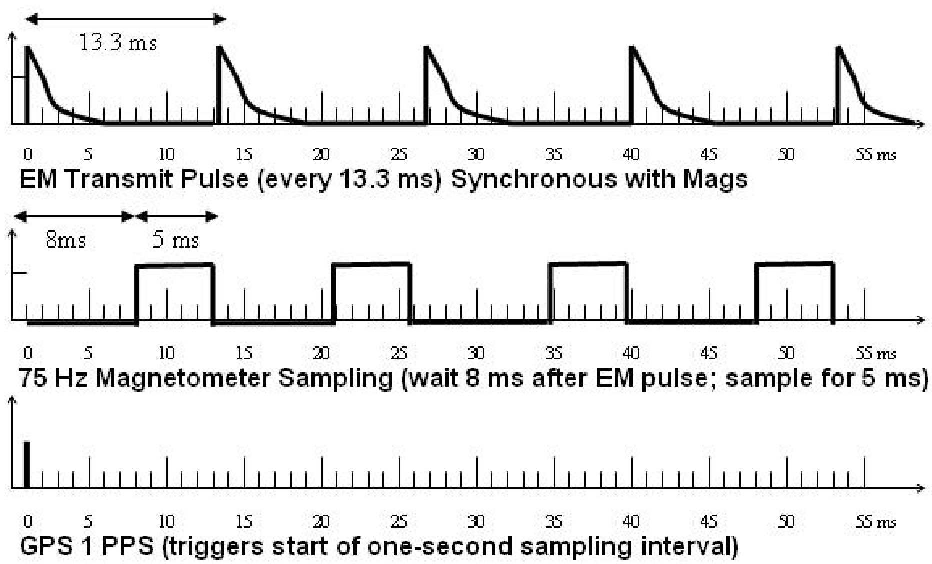

Figure 1. Conceptual Timing Diagram of Synchronous EM61 and Magnetometer Data Acquisition.
(Note that magnetometer sampling occurs only when EM61 transmission pulse has died down.)

2.2.2 Key Design Criteria

In addition to the interleaving electronics and software that sample the magnetometers after the secondary field induced by the EM61 pulse has rung down, the total system design that hosts both the magnetometers and the EM61s in a low-noise environment, utilizing a low-ferrous vehicle and a nonmetallic platform, is a key design factor.

2.2.3 Schematics, Figures, and Layout

The timing diagram for synchronous data acquisition is shown above in Figure 1. The system, showing the major components (low-ferrous vehicle, nonmetallic platform, GPS, magnetometer array, and EM61 array), is shown in Figure 2.

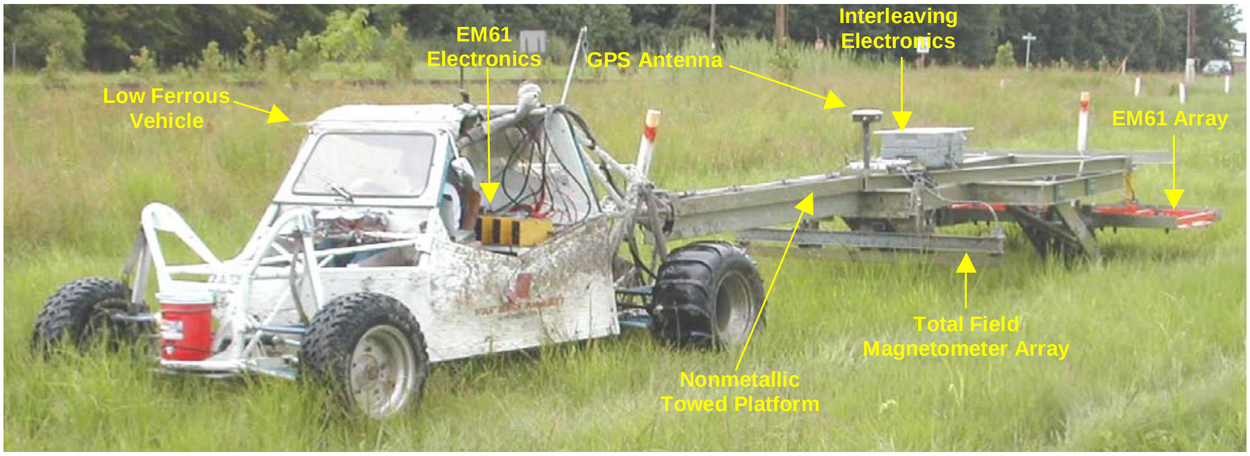

Figure 2. Layout of Major VSEMS Components.

2.2.4 Labor Requirements, Personnel, Training, and Ease of Use

Due to a safety requirement of having one field person in sight of the vehicle at all times, the long survey lines at the Kirtland Precision Bombing Range (PBR) required a three-man crew, with one driver and a flagger at the end of each line. A fourth analyst processed data in order to satisfy a requirement for next-day turnaround. Because portions of the system are 13 years old whereas other portions were only designed to survive a single 2002 Aberdeen Proving Grounds (APG) fielding, the system is best operated by a crew that includes one of its inventors and a UXO geophysicist. Through continuous incremental improvement and careful operation, the system has proven itself capable of reliably prosecuting large geophysical surveys.

2.2.5 Mobilization, Installation, and Operational Requirements

The system is transported by tractor-trailer to a site. A GPS base station is set up over a known control monument to provide the stationary link for the differential real-time kinematic (RTK), centimeter-level GPS. The survey site must be vehicularly navigable and have a clear view of the sky for GPS reception.

2.2.6 Performance

Because this project was part of the WAA Pilot Program, not a detection and clearance project, detection of individual targets was not the primary concern. Thus there was no performance metric for probability of detection. However, VSEMS detected the known bombing targets and previously unknown bombing targets on the site. The probability of false alarms in the 100% geophysical survey areas covered with VSEMS for which ground truth was obtained was 13.5%; these were no-finds largely correlated to geologic false alarms. In a post-survey analysis, if a confirming signature on both sensors is required for a detection, this probability of false alarm falls to 1%.

2.3 PREVIOUS TESTING OF THE TECHNOLOGY

The VSEMS technology is well-tested as described in the final reports for project MM-0208. Additional improvements and deployments of the technology include:

- *2003*—Incremental improvements funded by CEHNC (platform reinforcement)
- *2003*—VSEMS surveys 100 acres at Lowry
- *2003*—Incremental improvements funded by CEHNC (additional EM61 channels, larger EM61 coils, rugged computer, and additional platform reinforcement)
- *2003*—VSEMS surveys 100 acres at Portland International Airport
- *2004*—VSEMS surveys 100 acres at a mid-Atlantic housing site
- *2004*—Incremental improvements funded by EQT (new EM61 Mk2 array)
- *2005*—VSEMS surveys APG and Yuma Proving Grounds (YPG) test sites.

2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The complementary nature of sensors described above is one of the very things driving their concurrent use in VSEMS. The overriding advantage of the technology is the ability to *concurrently* collect both magnetometer and EM61 data in a single survey pass and thus compensate for each other's shortcomings. The Multisensor Towed Array Detection System (MTADS), in both its Naval Research Laboratory (NRL) and Blackhawk-fielded configurations, has a separate towed magnetometer and towed EM61 platform, and thus requires two separate surveys to acquire both mag and EM data sets. Further, since VSEMS sensors are mounted on a common rigid sensor platform, this all but ensures that the two sensors will run over the same ground locations, and thus essentially eliminates another problem of performing two separate surveys—that the data acquired in separate survey passes may not traverse the same objects in the same way, if at all, which may limit the efficacy of the data for discrimination algorithms. Note that in descriptions of data processing below, when we refer to the data being processed on a 10 cm grid, this refers to the use of in-house software to visualize the magnetometer and EM61 data and to invert the magnetometer data. However, when the magnetometer and EM61 data sets are each geolocated and processed and written out in an ASCII format for importation into Geosoft Oasis Montaj™, there is no 10 cm quantization of the geolocation data.

The main limitations of the technology as compared to MTADS are that the cross-track magnetometer spacing in MTADS is tighter than VSEMS (.25 meter versus .5 meter). The MTADS sensor platforms are instrumented to measure pitch and roll, and their data processing software uses these data to more accurately position sensor updates. However, note that these are limitations on the specific *implementation* of the technology as manifested in the current VSEMS. The core technology—interleaving acquisition of magnetometer data between EM61 pulses—does not have these limitations. The main limitation of the core interleaving technology is that it applies only to pulsed induction EM systems and is not applicable to frequency-domain EM systems. There are other competing technologies for concurrent magnetometry and EM (G-Tech, Blackhawk, Engineer Research and Development Center [ERDC]), but as of this date, none of them use a COTS industry-standard EM61, and none of them are conducting real-world 350-acre surveys.

There is an argument that the forward rate of advance of VSEMS is limited by the EM61's slower update rate (10 Hz as compared to 75 Hz for the magnetometer update rate), and thus the concurrent use of mags and EM61s is inherently less productive than magnetometers alone. We feel that, if all factors were equal, this would be true, but that all factors are almost never equal. For example, at the Kirtland survey, we could not have driven much faster than we already did while towing our prototype fiberglass platform. On extremely hospitable (e.g., soccer field) topography, the concurrent use of EM61s *will* limit speed, but this should be taken in the context of the list of other factors above.

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3.0 DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

The following were the primary performance objectives from the demonstration test plan. These were provided by the ESTCP Program Office for both of the ground-based systems on the WAA Pilot Program (e.g., MTADS and VSEMS).

Table 1. Primary Transect Performance Objectives/Metrics and Confirmation Methods Relating to Detection of Target Areas and Target-Free Areas.

Type of Performance Objective	Performance Criteria	Expected Performance (Metric)	Performance Confirmation Method	Actual Performance Objective Met?
Qualitative	Reliability and robustness	General observations	Operator feedback and recording of system downtime (length and cause)	System was reliable—Yes
	Terrain/vegetation restrictions	General observations	Correlation of areas not surveyed to available data (topographical maps, etc.)	System surveyed vehicularly navigable areas—Yes
Quantitative	Survey rate	12.5 acres/day	Calculated from survey results	9.5 acres/day—No
	Data throughput	All data from day x processed for anomalies and submitted by end of day x+1	Analysis of records kept / log files generated while in the field	Analyzed anomalies submitted by next day—Yes
	Percentage of assigned coverage completed	>95% as allowed by topography	Calculated from survey results	All transects completed—Yes 75% of 100% geophysical survey areas completed—No
	Transect location	95% within 2 m of requested transects	Calculated from survey results	98% of transects aligned after learning curve—Yes

These are discussed fully in Section 4.

The following were the secondary performance objectives from the demonstration test plan, again, as provided by the ESTCP Program Office.

Table 2. Secondary Transect Performance Objectives/Metrics and Confirmation Methods Relating to Characterization of Target Areas.

Type of Performance Objective	Performance Criteria	Expected Performance (Metric)	Performance Confirmation Method	Actual Performance Objective Met?
Qualitative	Ability of analyst to visualize targets from survey data	All targets in survey area identified	Data analyst feedback and comparison to 100% geophysical survey data/other demonstrators results	Targets readily visualizeable—Yes
Quantitative	Location of inverted anomalies	< 0.15 m horizontal < 30% vertical	Comparison to test strip ground truth	0.13 m horizontal, 0.20 m vertical—Yes
	Probability of false alarm	<5% of identified anomalies correspond to no ferrous metal source	Validation sampling (100% survey) and/or remediation sampling (digging)	13.5% correspond to apparent geology—No
	Signal-to-noise ratio (SNR) for calibration objects	+/- 10% of expected from Standardized UXO Technology Demonstration Site performance	Comparison of calibration objects results to documented Standardized UXO Technology Demonstration Site performance	Inconsistent—No
	Data density	> 15 pts/m^2	Calculated from survey results	Average 22 pts/m^2—yes

These are discussed fully in Section 4.

3.2 SELECTION OF TEST SITE

The Former Kirtland PBR was selected by the ESTCP Program Office due to a combination of size, topography, and development pressure. It was a nearly ideal site for use of a ground-based system on a WAA Pilot Program, as the topography was extremely hospitable to ground-based vehicular technology.

3.3 TEST SITE/FACILITY HISTORY/CHARACTERISTICS

The Kirtland PBR FUDS that contains the ESTCP WAA site is approximately 16,000 acres, encompassing multiple target areas. It is located west of Albuquerque, New Mexico, and served as a training area for Kirtland Air Force Base during WWII. The WAA Pilot Program was conducted on two parcels totaling 5,000 acres on either side of Double Eagle Airport. The study area is known to contain three PBRs and an additional simulated oil refinery target. Munitions known or suspected to have been used on the site include 100-lb practice bombs and 250-lb high explosive bombs. A certificate of clearance was issued for one portion of the site, Target N3. It is reported that 17,000 lbs of scrap were stored in this area. Currently, the WAA study area is undeveloped. Portions are planned for commercial or industrial development within the next decade, and airport expansion into these lands is possible.

3.4 PHYSICAL SETUP AND OPERATION

The equipment was mobilized via tractor trailer from Newton, Massachusetts and arrived in Albuquerque on September 20, 2005. Upon arriving at the site, a lockable CONEX box was procured, large enough to allow VSEMS to be driven inside without disassembling the system. Pre-arranged office space at the Double Eagle Airport was inhabited. GPS base station monuments were located, as was the test strip that had been emplaced by the ESTCP Program Office and representatives from CEHNC. The daily routine included inspecting and maintaining the system, surveying the test strip, verifying the results, locating and then surveying the required transects or 100% geophysical survey areas as directed by the ESTCP Program Office, surveying the test strip a second time, storing the equipment overnight, and processing and analyzing the data to provide the desired next-day turnaround for transect results. The survey was accomplished in two legs. The first ran from September 9, 2005 through October 10, 2005; the second ran from November 7, 2005 through November 11, 2005.

3.5 ANALYTICAL PROCEDURES

Location and design of transects was performed by another contractor running Visual Sample Plan (VSP). Selection of 100% geophysical survey areas was performed by the ESTCP Program Office.

The magnetometer data were geolocated using data from the GPS. They were lightly median-filtered to remove spikes, notch-filtered to remove the 15 Hz sine wave that comes from the 60 Hz ambient electrical hum from the power grid that, due to the system's 75 Hz sampling, aliases at 15 Hz. The data were then passed to a dynamic background filter that determines the median of a 6-sec window, then subtracts that median value from the data. This effectively removes large-scale geology, the remnant signature of the vehicle, and diurnal drift from the data. The data were then gridded on a 10-cm grid and visualized.

The EM61 data were geolocated using the data from the GPS. Successive GPS updates were smoothed and used to determine heading. The heading, platform geometry, and GPS position were used to determine the positions of the centers of all five EM61 1x.5 m coils. The EM61s were powered by two large car batteries and were zeroed in the field in the morning and after lunch. This combination resulted in data with a minimum of drift, and as such, gross background leveling of the EM61 data was not necessary for visual anomaly detection on the transect surveys. Like the magnetometer data, the EM61 were gridded on a 10 cm grid and visualized. For 100% geophysical surveys, the EM61 data were background-leveled in Geosoft Oasis Montaj using a nonlinear filter.

Magnetometer data and EM61 data were visualized simultaneously using custom software that allows simultaneous panning, zooming, and scrolling through both data sets. The operator then enters a "likelihood" value intended to broadly triage candidate anomalies into three different classes. Likelihood 2 anomalies are those that the operator feels are of a size and shape consistent with whole MEC. These typically have magnetic signatures that are classic dipoles with a clear, round, strong, well-defined positive lobe and a clear, mushroom-cap-shaped, strong, well-defined negative lobe. The operator looks at both magnetometer and EM61 data and uses his judgment when making the likelihood determination. The anomaly may have a weak or no

magnetic signature but may still be flagged as Likelihood 2 if the EM61 signal is broad and strong enough. Likelihood 0 anomalies are those that the operator feels are due to noise or geology in either the magnetometer or EM61 data. Likelihood 1 anomalies are those that are neither Likelihood 2 or Likelihood 0. These are generally anomalies that have a discernible signature in the magnetometer and/or EM61 data but are not the largest, strongest anomalies in the data set and are smaller and/or weaker than the candidate anomalies in the test strip. In analysis of the 100% geophysical survey areas, the constraints for Likelihood 2 targets were relaxed to include targets that probably were geology. This was done intentionally to ensure that some targets that appeared geologic in nature to the analyst would be dug to determine if that was, in fact, correct.

In addition to processing in our own software, the magnetometer and EM61 data sets were brought into Geosoft Oasis Montaj. Project files, database files, grid files, map files, and geotiff files were created and delivered to the Program Office.

4.0 PERFORMANCE ASSESSMENT

4.1 PERFORMANCE DATA

The overarching goal of project MM-0531 was to use the ESTCP-funded VSEMS in whatever way ESTCP directed us to use it to be of value to the WAA Pilot Program. Vehicle towed arrays clearly have their place in wide area, as they go places helicopters cannot, and detect the smaller objects that are beyond the detection limit of helicopter-based magnetometry. The benefits of using a *concurrent multisensor towed array* are that (1) since most common geology ("hot rocks") don't show up on the EM61, the presence of a confirming EM signature can be used as a highly effective geologic false alarm reduction tool and (2) many sites contain surprises in the form of ordnance that may not have been listed as historically used, so choosing a sensor because of its detection characteristics (for example, mags because of the ability to detect large objects deep) may result in missing unexpected objects (for example, small projectiles that have very little signature on the magnetometers). The use of VSEMS had both these advantages.

4.2 PERFORMANCE CRITERIA

The following were the primary performance objectives from the demonstration test plan (these are also listed in Ssection 3.1):

Table 3. Primary Transect Performance Objectives/Metrics and Confirmation Methods Relating to Detection of Target Areas and Target-Free Areas.

Type of Performance Objective	Performance Criteria	Expected Performance (Metric)	Performance Confirmation Method	Actual Performance Objective Met?
Qualitative	Reliability and robustness	General observations	Operator feedback and recording of system downtime (length and cause)	System was reliable—Yes
	Terrain/vegetation restrictions	General observations	Correlation of areas not surveyed to available data (topographical maps, etc.)	System surveyed vehicularly navigable areas—Yes
Quantitative	Survey rate	12.5 acres/day	Calculated from survey results	9.5 acres/day—No
	Data throughput	All data from day x processed for anomalies and submitted by end of day x+1	Analysis of records kept/log files generated while in the field	Analyzed anomalies submitted by next day—Yes
	Percentage of assigned coverage completed	>95% as allowed by topography	Calculated from survey results	All transects completed—Yes 75% of 100% geophysical survey areas completed—No
	Transect location	95% within 2 m of requested transects	Calculated from survey results	98% of transects aligned after learning curve—Yes

The following were the secondary performance objectives from the demonstration test plan (also listed in Section 3.1):

Table 4. Secondary Transect Performance Objectives/Metrics and Confirmation Methods Relating to Characterization of Target Areas.

Type of Performance Objective	Performance Criteria	Expected Performance (Metric)	Performance Confirmation Method	Actual Performance Objective Met?
Qualitative	Ability of analyst to visualize targets from survey data	All targets in survey area identified	Data analyst feedback and comparison to 100% geophysical survey data/other demonstrators results	Targets readily visualizeable—Yes
Quantitative	Location of inverted anomalies	< 0.15 m horizontal < 30% vertical	Comparison to test strip ground truth	.13 m horizontal, .20 m vertical—Yes
	Probability of false alarm	<5% of identified anomalies correspond to no ferrous metal source	Validation sampling (100% survey) and/or remediation sampling (digging)	13.5% correspond to apparent geology—No
	SNR for calibration objects	+/- 10% of expected from Standardized UXO Technology Demonstration Site performance	Comparison of calibration target results to documented Standardized UXO Technology Demonstration Site performance	Inconsistent—No
	Data density	> 15 pts/m^2	Calculated from survey results	> 22 pts/m^2—Yes

4.3 DATA ASSESSMENT

Tables 3 and 4 are discussed below.

Primary Metrics

Reliability and Robustness: The system's reliability and robustness were generally good for a prototype system. During the 8-week survey, 2 full days were lost to downtime. One was due to a battery charger malfunctioning and boiling the acid in the vehicle batteries, necessitating their immediate replacement. The other was due to chasing down and solving a noise problem on the magnetometers because of a current ground loop. The proof-of-concept fiberglass towed platform degraded during the survey but continued to function. Near the end of one survey day, one end holding the EM61 array broke completely. Subsequently, we inspected the platform every morning and replaced any missing rivets with bolts, with no further downtime due to platform malfunction. Note that this platform was constructed as part of the original ESTCP MM-0208 project and was intended for a single survey at APG. The platform was retired at the end of this project, having surveyed nearly 1,000 acres, and has been replaced by a carbon fiber platform with an engineered suspension.

Terrain/Vegetation Restrictions: There were very few terrain or vegetation restrictions; the former Kirtland PBR was generally a flat, open area with low, scrubby vegetation. The main

restrictions came from several fence lines cutting across the site, preventing some of the transects from being followed exactly as planned.

Survey Rate: The average survey rate was 9.5 acres per day. This was averaged over all survey days, including days when GPS interference severely hobbled productivity, down days, and days when we switched from transects to 100% geophysical surveys. The persistent jamming of the GPS base-to-rover radio link was the single largest factor affecting productivity. Despite locating the GPS base station in the northwest corner of the site (the highest point), using a scanner to find an open channel, and putting the base station radio antenna on a 30-ft high mast, on most days the base/rover link would be severed when another differential GPS system in the valley was switched on; we could hear the interference on the previously unused channel on our scanner. We would then have to locate a new clear channel with the scanner, drive up to the base station in the corner of the site and change the channel, and do the same in the rover. On some days, this procedure had to be repeated two or three times. On days when interference was minimal, the system and personnel were certainly capable of high productivity; 9 days were over 12.5 acres per day, 6 were over 15, and 1 was over 20.

Data Throughput: Data was analyzed and anomaly lists were supplied to the ESTCP Program Office by the end of the next day.

Percentage of Assigned Completed Coverage: All of the planned transects were covered (with the exception of N/S transects though the northwestern corner of the site that were deleted by the Program Office due to the fact that the Simulated Oil Refinery Target (SORT) already had been located using the earlier transects). All the 100% geophysical survey areas were surveyed, but in acreage, 75% of the assigned areas were completed because the first three assigned 100% geophysical survey areas were 30 acres each, and we were initially instructed to survey as much of each one as could be completed in a day. All subsequent 100% geophysical survey areas were 100% surveyed.

Transect Location: Transect locations from the first 2 days were off by as much as tens of meters due to learning curve issues in programming and following the track guidance equipment in the vehicle, but subsequently, the geodetically located sensor swath overlaid the planned transects in nearly all data sets. A numerical off-track metric was obtained by calculating for every transect the average orthogonal distance from the nearest planned transect. These results are shown in Figure 3. The degree to which track following improved enormously after the second day is clear. The magenta line represents the 2-m metric. When including the poor results from the first 2 days, the percentage of tracks within 2 m of the planned tracks is 93%, just missing the 95% metric, but if these learning-curve days are excluded from the calculation, 98% of the tracks are within the metric; 81% of the tracks were within 1 m of the planned transects; and 53% were with ½ m.

Secondary Metrics

Ability to Visualize Targets: Targets (both individual anomalies and entire bombing targets) were readily visualizable in VSEMS survey data.

Location of Inverted Anomalies: Unfortunately, no independent measurement was made of the actual location of the ground truth items that were dug. In the absence of this information, we

analyzed the location accuracy of the test strip items and found it within 13 cm horizontally and within 20 cm vertically.

Probability of False Alarm: The false alarm issue was discussed in detail in the Final Report. Because VSEMS concurrently collects both magnetometer and EM61 data, at the Kirtland site it provided the potential for an experienced operator to exclude many, if not most, geologic anomalies.

Signal to Noise for Calibration Objects: The signal from calibration objects was not sufficiently consistent to meet the desired metric, but this is more a reflection of platform motion than it is a symptom of anything wrong. This was discussed in detail in the Final Report. One example is shown in Figure 3. The strongest item in the calibration test strip was item 12, the 155mm shell at 90 cm depth. The run-to-run plots are displayed in the figure. The blue plot is raw peak magnetometer data in a pre-set area of interest over the object; the magenta plot is the peak value of the inverse-modeled (fit) data over the object; and the yellow plot is the raw peak EM61 gate 3 value. On this plot, the raw magnetometer data range from 449 to 557 nT, which is close to being consistent to within +/- 10%. However, the plots for other weaker objects show data that are less consistent.

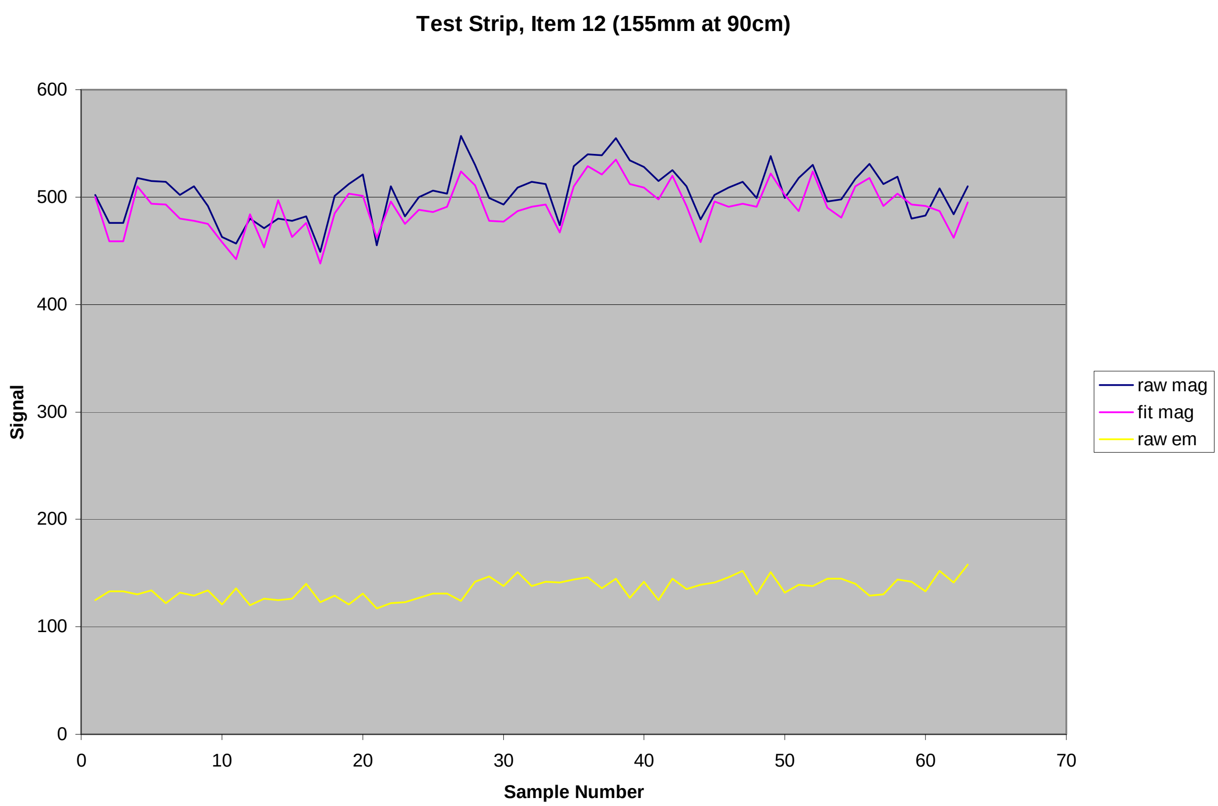

Figure 3. Test Strip Data, Raw EM Value (yellow) **and Raw and Fitted Mag Values** (blue and magenta) **for 155 mm Projectile at 90 cm Depth.**

Additional Performance-Related Issues
While we were analyzing the Kirtland data, we felt that the presence of a good, strong, classically dipolar magnetometer signature, coupled with the absence of a confirming EM61 signature, indicated an object too deep for detection by the EM61 (this was, after all, a bombing range; the possibility of objects too deep for EM61 detection was not an academic one). However, with the benefit of dig results from the 100% geophysical survey areas, we now see that the overwhelming majority of these signatures turned out to be no-finds—almost certainly geologic false alarms. In the Final Report, we examined these no-finds (largely due to geologic false alarms) and showed that requiring the presence of a confirming signature on the EM61 dropped the no-find rate from 13.5% to 1%. This shows the utility of a concurrent multisensor system in reducing geologic false alarms. We also presented data from Area 2a near the SORT where large, circular features ("crop circles") were apparent only in the EM61 data and not in the magnetometer data. The centers of these circles correlate exactly with the centers of grid squares that show up in the Laser Imaging Detection and Ranging (LIDAR) data. This shows the utility of a concurrent multisensor system in detecting unexpected signals that may aid in WAA.

4.4 TECHNOLOGY COMPARISON

There are no other concurrent mag/EM61 vehicular systems. The other vehicle-towed arrays which have non-simultaneously deployed EM61 and magnetometer platforms are (1) the original NRL-fielded MTADS and (2) the Blackhawk (now Zapata)-fielded MTADS. Neither are concurrent mag/EM systems. Technically, the NRL MTADS is not a commercially available system but a system for scientific study, and is usually fielded by a large crew of scientists and engineers on jobs intended to showcase the system's ability to collect discrimination-quality data. The Blackhawk-fielded MTADS was intended to be the commercially available version of the NRL-developed MTADS; we do not know if it is still in use. The NRL MTADS is generally accepted to be the gold standard for data quality due to its .25-cm magnetometer spacing (VSEMS has a 50-cm magnetometer spacing), high-output EM61 transmitters, rigorously tested system timing, and the additional GPS units and inertial navigation unit used to accurately position the data from the EM61 array.

EM61-Only Towed Arrays: Members of the National Association of Ordnance Contractors (NAOC) with vehicle-towed EM61-only arrays include Parsons, Sky Research, USA Environmental, Weston Geophysics, Naeva, the ARM Group, Shaw, Tetra Tech, SAIC (a different division than the one fielding VSEMS), and UXB. We are not familiar with every one of these systems, but we know how difficult it is to correctly deal with the system timing issues necessary to collect correctly geo-located data.

Magnetometer-Only Towed Arrays: The only NAOC members with vehicle-towed magnetometer-only arrays are Sky Research and ARM. The smaller number of towed magnetometer systems is due to several factors, including the preponderance of statements of work from the USACE that mandate use of an EM61; the historical reliance of towed magnetometer arrays on expensive custom vehicles with low magnetic signatures (this has been evaluated in ESTCP Project MM-0605, which has concluded that there are COTS vehicles that work nearly as well for towed array magnetometry as the custom vehicles); and the necessity of a well-engineered system due to the sensitivity of magnetometers to any nearby ferrous metal. Our understanding is that both the Sky and the ARM system are well-engineered systems that pay appropriate attention to timing and signature issues and generate high-quality data.

Since VSEMS uses COTS EM61s and total field magnetometers, there is little about VSEMS data streams that individually distinguish them from mag or EM61 data or from properly synchronized data acquired by the above contractors. Although these sensors have a broadly overlapping detection envelope, the nod generally goes to EM61s for sites where the objects of interest are small (20 mm and 40 mm), even though the EM61's 10 Hz output rate limits the survey speed. Conversely, for the WAA objectives of detecting extent of bombing targets contaminated with air-dropped munitions, magnetometers were the sensor of choice, even though the magnetometer's response to geology can limit the interpretability of the data. Geology was not expected to be a problem at the Kirtland PBR, but it was. An analysis in the Final Report shows that the EM61 was unaffected by this geology, and since VSEMS was driven slowly in order to collect high-quality EM61 data anyway and there were no deep mag-only objects recovered at Kirtland, one could argue that an EM61-only survey by a commercial contractor with a well-synchronized array would have been sufficient at Kirtland. However, the absence of deep mag-only objects is likely a function of the lack of digging of the target centers themselves. Indeed, finding a live 250-lb bomb would have proven problematic at Kirtland, as such a discovery probably would have necessitated closure of the Double Eagle Airport.

Similarly, use of a mag-only vehicle-towed array carries with it the risk that the area, like Kirtland, has unexpected geology. At the WAA survey at the Victorville PBR Y site, the MTADS magnetometer platform encountered unexpected magnetic geology, requiring additional surveying with man-portable EM61 equipment. Use of simultaneous mag/EM at this site would have concurrently acquired this EM61 data and obviated the need for a separate EM61 survey.

Helicopter-Based Magnetometry: If the site is large, flat, and free of obstructions, and MEC is inside heliomag's detection envelope (60 mm and above), and geology does not interfere with the magnetometers, helicopter-based magnetometry can acquire hundreds of acres in a day and completely cover the site. For target delineation of an impact area of air-dropped major caliber ordnance, vehicular traverses may add little to the complete picture provided by heliomag. However, note that heliomag had the same problems with geology at the Victorville PBR Y site that ground-based magnetometry had, resulting in a separate ground-based EM61 survey to help characterize which anomalies were geologic in origin. Note also that helicopter-based magnetometry did not detect the "crop circles" in Area 2A at Kirtland that helped to resolve the location of the SORT. These large circular features that correlated with a grid pattern in the LIDAR data were only present in the ground-based EM61 data.

5.0 COST ASSESSMENT

5.1 COST REPORTING

5.1.1 Cost of the Demonstration at Kirtland Program Requirements Review (PRR)

A by-task cost of performing the demonstration of VSEMS at the Kirtland PBR consists of the following:

- The cost of reinforcing the proof-of-concept fiberglass platform to help it survive the survey
- The cost of mobilization/demobilization (driving the tractor/trailer to and from Albuquerque)
- The cost of a 5-week and a 3-week survey stint in Albuquerque
- The cost of analyzing the data back at SAIC
- The cost of project management and report writing.

The actual breakdown by task is below. Mob/demob includes driving the tractor/trailer from Newton, Massachusetts to Albuquerque, New Mexico and back, plus travel for the crew for the two separate mobs. The Survey task includes the four-man crew on site for 40 days, plus all related survey other direct costs (ODCs). The Analysis task includes the time spent analyzing the 100% geophysical survey data after the actual on-site survey. It also includes the costs of training in Geosoft Oasis Montaj and AETC's UxAnalyze plug-in, and the time spent analyzing EM61 data. The project management task includes the site visit, all meetings and presentations, classical project management, and reporting. SAIC's VSEMS already includes the tow vehicle, towed platform, magnetometers, EM61s, GPS, and computers. As such, none of these items needed to be purchased for this project. An Explosive Ordnance Disposal (EOD)-qualified escort from Explosive Ordnance Technologies Inc. (EOTI) was provided by the ESTCP program Office and acted as the fourth member of the field crew; his estimated costs are included in the costing.

Table 5. Cost Breakdown by Task of the Kirtland PBR Demonstration.

Reinforce Platform	$ 11,458.06
Mob/demob	$ 27,507.75
Survey	$ 226,366.58
Analysis	$ 34,436.61
Project management	$ 66,063.95
Total	$ 365,832.95
Number of Acres	5000
Cost per acre	$73

5.1.2 Cost of a Real-World Implementation at the Scale of the Demonstration

For a commercially contracted site of like size, costs would be similar with the following exceptions.

- The towed platform would not need to be reinforced, as it has already been replaced with a redesigned, more robust version.
- The four-man crew would be reduced to a three-man crew. One factor driving the crew size was the de facto safety requirement of having the survey vehicle in sight of a crew member at all times. The long survey lines at the Kirtland PBR thus required crew members at each end. Crew reduction is possible by having the data analyst double as a member of the field crew, processing the previous day's data on a laptop computer in his support vehicle while having the vehicle positioned at one end of the survey area to allow line-of-sight to the survey vehicle.
- The method of inverting anomalies in the EM61 data, which included learning curve issues in both Oasis Montaj and UxAnalyze, would probably not be repeated (that is, there was clear value in using the EM61 to screen out geologic false alarms that didn't appear in the EM61 data, but there was not clear value in inverting every EM61 anomaly).
- The meetings, presentations, and reporting requirements would be substantially less than in an ESTCP project.

For this section we estimate cost of covering 2% of a 10,000 acre site with transects. For the estimate below, we assume a 1,500 mile mobilization, a three-man crew, a survey rate of 12 acres per day, one prove-out day, and half a day of analysis per field day.

Table 6. Projected Cost Breakdown for 2% Survey of 10,000 Acres.

2% of 10,000 Acres			
	cost	units	subtotal
Mob/demob three-man crew	$22,046	1	$22,046
DGM* three-man crew	$6,877	18	$123,786
Processing and analysis	$1,520	9	$12,920
Total cost			$158,752
Cost per acre			$16

*DGM = digital geophysical mapping

5.1.3 Cost Extrapolated to a Full-Sized Site

As per instruction from the Program Office, for this section we estimated the cost of covering 2% of a 50,000 acre site with transects. For the estimate below, we again assume a 1,500 mile mobilization, a three-man crew, a survey rate of 12 acres per day, one prove-out day, and half a day of analysis per field day.

Table 7. Projected Cost Breakdown for 2% Survey of 50,000 Acres.

2% of 50,000 Acres			
	cost	**units**	**subtotal**
Mob/demob three-man crew	$22,046	1	$22,046
DGM three-man crew	$6,877	85	$584,545
Processing and analysis	$1,520	42	$63,840
Total cost			$670,431
Cost per acre			$13.4

5.2 COST ANALYSIS

For commercial survey work, we employ daily equipment usage charge that is $2,000/day. The daily rental charge is waived for research projects such as WAA.

In an MTADS cost and performance report, they estimated the replacement cost of their vehicular system at roughly $800,000. SAIC recently had the opportunity to quote a new multisensor vehicular system, and came up with a similar return on management (ROM) for the replacement cost.

In projecting cost for a commercial survey, it cannot be stressed enough that each site and project has different requirements that cannot be anticipated, making an accurate cost estimate impossible without a detailed statement of work.

5.2.1 Major Cost Drivers

Mob/Demob: VSEMS (buggy, towed platform, and all support equipment) is transported in a 32-ft trailer owned by SAIC. While in the field, the trailer is used for maintenance, storage, and data processing. The tractor-trailer is professionally driven to the site by a certified truck driver who is a part-time SAIC employee and who frequently stays as part of the survey field crew.

Labor: Surveys can be performed using a crew of as few as two people. This is sufficient except when survey transects are difficult to see due to site size or terrain. When necessary, additional “flaggers” have been employed, sometimes as local temporary labor, to hold flags to help the vehicle driver to see his previous transect. Although the recent incorporation of a COTS track guidance system into VSEMS largely eliminates the need for dedicated flaggers, the long lines used on the WAA surveys resulted in a de facto requirement that the vehicle be in sight at all times, and this required people at each end of the line. For surveys on active UXO ranges contracted through the Army Corps of Engineers, a higher level of on-site EOD support is mandated. At the Kirtland survey, the on-site EOD person was supplied by the ESTCP Program Office and manned one end of the survey line. The requirement for next-day turnaround of results required that the data analyst not be in the field as a flagger but instead be analyzing data. The combination of all the above factors resulted in a four-man crew at Kirtland, but we are assuming a three-man crew in the cost estimates above because the data analyst can process data in a pre-positioned support vehicle at one end of the survey site with line-of-sight to the survey vehicle. Lastly, at Kirtland, the analyst was the principal investigator (PI). We priced the PI into

the above commercial cost estimates, but his presence is not strictly required; thus, actual survey costs will probably be lower.

In addition to mob/demob and labor, the major cost drivers are the vehicular hospitability of the survey site and the amount of time actually spent collecting data. At the Kirtland PBR, VSEMS drove slowly due to the proof-of-concept nature of the fiberglass towed platform and the need to maintain adequate EM61 data quality. GPS operation had a major impact on productivity; the radio link between the GPS base and rover was routinely jammed by the booming construction trade in the valley below, necessitating our changing the radio channel sometimes several times a day. With these limitations, we acquired in excess of 15 acres on days where acquisition continued without interruption. We used a 12-acre-per-day productivity estimate for the cost extrapolations above.

Data Processing: The elasticity of data processing and analysis requirements is a major factor that can contract or expand cost. Since VSEMS acquires both mag and EM61 data, both data streams must be corrected, processed, and analyzed. Typically, most preprocessing and correction can be done in an on-site, same-day fashion, resulting in Oasis-viewable data without additional back-in-the-office analysis time. If individual target analysis is required, a ROM of one analysis day per field day is often employed on production jobs. For the above estimates, we have compromised and assume ½ a day of processing and analysis per field day.

5.3 COST COMPARISON

The technology comparison section above lists the pros and cons of magnetometer-only and EM61-only approaches, and names the NAOC contractors with such capabilities. Immediately above, we have listed our own major cost drivers. These are known from use of VSEMS on both research and commercial surveys. It is difficult for us to project other contractor's costs; instead, we will make relative cost comparisons. In the discussion below, we have removed the two cost drivers of VSEMS' comparatively high mob and labor costs, as these have more to do with SAIC's implementation of VSEMS and less to do with concurrent mag/EM per se.

If the survey site was large and free of obstructions and the objects of interest were large (e.g., 155-mm projectiles, 250-lb bombs, etc), and the geology was known to be inert to the magnetometers, then we would expect helicopter-based magnetometry to be the most cost-effective approach.

As the number of obstructions and the topographical undulations increase and as the site size shrinks, we would expect the cost effectiveness of towed magnetometry to overtake it. Because the magnetometers output data at a faster rate than the EM61s, a towed magnetometer array can be driven faster than a towed EM61 array and maintain a sufficiently high down-track data density. For a soccer-field-smooth site, this can result in a real productivity difference between mag and EM, but whether a site's topography is sufficiently smooth to allow it to actually be driven at a higher speed is extremely site-dependent. With concurrent mag/EM, the survey speed needs to be such that it produces high-quality data for both sensors, and since the EM61 output rate is slower, it is the EM61 that affects survey speed for concurrent mag/EM. Again, whether this is the major determining factor of productivity is highly site-dependent. But, for this reason, the cost of a VSEMS survey is expected to be higher than a mag-only towed array survey. In the

Final Report, we presented data showing that, if the strategy is to detect large objects by using the magnetometers as the primary sensor and use the EM61s to screen out geologic false alarms, the system could be driven faster and still collect EM61 data of sufficient quality to help screen out geology. In this case, we would expect the deployment costs to be the same, VSEMS' processing and analysis costs to be slightly higher, and this higher cost to be offset by reduced dig costs.

If the objects of interest are small- to medium-sized, or the site is known to have geology that affects the magnetometers, then EM61s would be the sensor of choice, even though, all factors being equal, the forward rate of advance and thus the daily production rate is potentially less than magnetometers. Assuming identical survey speeds, the cost of an EM61-only survey is expected to be the same as a VSEMS survey, though VSEMS processing and analysis costs would be slightly higher. We would expect a benefit to come from the additional deeper mag-only detections (and we do see these detections in real production surveys), but it is difficult to put a dollar value on this benefit.

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6.0 IMPLEMENTATION ISSUES

6.1 COST OBSERVATIONS

Terrain: The economics of surveys bid at a fixed acreage rate per day depends on coverage rate. Smooth, grassy areas that have already been run over by heavy equipment are far more vehicularly navigable than rocky or stumpy areas, and lower coverage rates engender higher survey cost. This is particularly true due to the proof-of-concept nature of the fiberglass towed platform, which had no suspension and thus had to be treated gently. The Kirtland PBR was a very hospitable site in terms of terrain.

GPS Coverage: The major surprise in terms of productivity was the degree of difficulty maintaining GPS coverage across the site. Because the site was physically large, we employed high-power, 35-watt, long-haul GPS radios in the UHF band, as these allow a range as high as 6 miles. We erected a tower in the highest corner of the site to maximize coverage and left it there for the entire survey, lessening daily setup and tear-down time. However, UHF radios have only a finite number of channels, and they do not automatically frequency-hop between channels. Whenever a construction crew in the valley below us began using a GPS (and there were many such construction crews; using our scanner, we could hear them fire up their radios), the channel would be jammed and we would need to hunt for a new clear channel. This required driving several miles up to the GPS base station to manually switch channels. In the future, we would be sure to also have 900 MHz spread spectrum frequency hopping radios. These do not have the long range that the UHF radios do, but either by deploying multiple base stations or using repeaters, these radios could eliminate jamming problems that plagued us.

Forward Rate of Advance: Though the terrain was friendly at Kirtland, forward rate of advance was limited by the somewhat fragile towed platform. This has since been replaced with a newly designed carbon fiber platform with an engineered suspension. In addition, the 10 Hz EM61 update rate imposes speed constraints, as data quality degrades with increased down-track data separation.

Expert On-Site Presence: The PI, Robert Siegel, has accompanied VSEMS on all of its surveys. This ensures a minimum of downtime and the delivery of a high-quality product but carries with it a high cost. Due to improvements to the system, this expert, on-site presence is less and less necessary over time.

6.2 PERFORMANCE OBSERVATIONS

In terms of surveying desired transects and 100% geophysical survey areas, locating evidence of bombing targets, and reporting results next-day, the system performed very well. As above, productivity did not reach the 12.5 acre/day metric due to a number of factors, chief among them being GPS issues. The probability of false alarm of 13.5% exceeded the 5% metric due to no-find digs caused by geology, but this can be reduced to 1% by requiring a confirming signature on the EM61 in order to exclude geology.

6.3 SCALE-UP

As the very nature of WAA is large-scale, there are no scale-up issues.

6.4 END-USER ISSUES

Because the technology involves combining the two sensors most validated against UXO for digital geophysical mapping—total field magnetometers and EM61 pulsed induction coils—there are no specific end-user issues above those that apply to all DGM data.

6.5 APPROACH TO REGULATORY COMPLIANCE AND ACCEPTANCE

Because the technology involves combining the two sensors most validated against UXO for digital geophysical mapping—total field magnetometers and EM61 pulsed induction coils—there are no specific regulatory hurdles beyond those that apply to all DGM data.

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APPENDIX A

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